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# Large scale applications of HTS in New Zealand

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**Abstract**

New Zealand has one of the longest-running and most consistently funded (relative to GDP) programmes in high temperature superconductor (HTS) development and application worldwide. As a consequence, it has a sustained breadth of involvement in HTS technology development stretching from the materials discovery right through to burgeoning commercial exploitation. This review paper outlines the present large scale projects of the research team at the newly-established Robinson Research Institute of Victoria University of Wellington. These include the construction and grid-based testing of a three-phase 1 MVA 2G HTS distribution transformer utilizing Roebel cable for its high-current secondary windings and the development of a cryogen-free conduction-cooled 1.5 T YBCO-based human extremity magnetic resonance imaging system. Ongoing activities supporting applications development such as low-temperature full-current characterization of commercial superconducting wires and the implementation of inductive flux-pump technologies for efficient brushless coil excitation in superconducting magnets and rotating machines are also described.


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*Keywords:* High-temperature superconductors; Large-scale applications; Roebel cable; HTS transformer; HTS magnetic resonance imaging; Cryogen-free magnets; Wire characterization; Flux pump; Commercialization

## 1. Introduction – History of HTS Research in New Zealand

New Zealand has a long history of achievement in high temperature superconductor (HTS) materials research and subsequent applications development, spanning from the initial identification of the $Bi_2Sr_2Ca_2Cu_3O_{10+x}$ (Bi-2223) first generation (1G) HTS material [1,2] to the present-day commercial supply of HTS magnets and systems, cables and components through the companies HTS-110 Ltd. [3] and General Cable Superconductors Ltd. [4], supported by an extensive local supply chain. In 1987, Dr Bill Robinson (1938–2011), then Director of the Physics and Engineering Laboratory (PEL) of the New Zealand Government Department of Scientific and Industrial Research (DSIR), put his weight behind a rapidly evolving research programme in PEL into high temperature superconductors. His foresight and encouragement enabled the establishment of a leading R&D position, which was maintained through the reconstitution of PEL into Industrial Research Ltd. (IRL) in 1992. The newly-established Robinson Research Institute of Victoria University of Wellington [5] that fittingly bears his name now houses the former IRL Superconductivity and Energy Group following the dissolution of IRL by the Government in 2013. Under these new auspices, the team continues its drive to further discover, develop and successfully commercialize high temperature superconducting technologies for the benefit of society.

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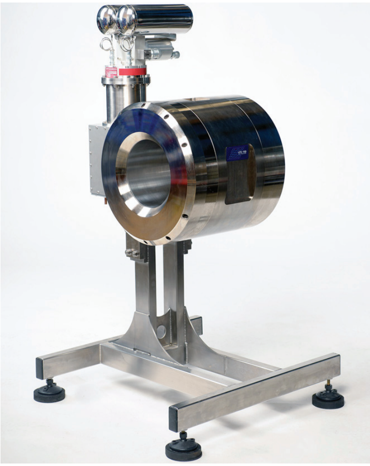

Fig. 1. 1.5 T cryogen-free conduction-cooled 2G HTS MRI magnet.

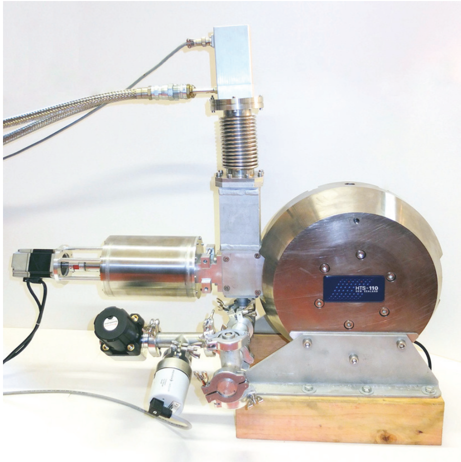

Fig. 2. Flux pump retrofitted to a 2 T HTS NMR relaxometry magnet.

## 2. Coil-based Technologies

### *2.1. HTS magnetic resonance imaging (MRI)*

We have built a demonstration conduction-cooled (20 K) cryogen-free 1.5 T human extremity magnetic resonance imaging system (Figure 1) utilizing approximately 5 km of second generation (2G) AMSC Amperium® YBCO wire to generate better than a 50 ppm peak-to-peak field homogeneity over a 115 mm diameter spherical volume, sufficient for clinical extremity imaging [6]. Design choices include the use of unshielded gradient coils for a significant reduction in magnet bore diameter, minimizing the quantity of expensive 2G wire required. Further benefits of this design choice include greatly reduced power consumption, thereby reducing gradient coil and shim heating, as well as a simpler construction process. These come at the cost of increased gradient–magnet interactions through the formation of eddy currents, resulting in magnet coil heating and changes in the magnetic resonance signal phase. These have been shown to be surmountable through careful magnet design, however, with a less than 1 K magnet coil temperature rise over a full day of routine imaging, and the ability to correct the magnetic resonance signal using standard pulse pre-emphasis techniques [7]. Long-term temporal stability of the magnetic field has been established to around 1 ppm through active thermal stabilization of the warm iron yoke used for shielding, while field hysteresis due to screening currents formed in the YBCO on thermal or field cycling has been shown to be small and reproducible, and therefore able to be compensated by passive shimming. We have thus shown that clinical-grade MRI is possible using an HTS magnet operating in driven mode.

HTS magnets are attractive for MRI applications due to their capabilities for "push-button" field ramping and fast recovery from power outages, which make them particularly suitable for mobile deployment, or for deployment in locations with substandard service infrastructure. Our future design targets include a 3 T bench-top pre-clinical MRI system and a design concept for a containerized mobile whole-body MRI using $MgB_2$ in driven mode.

### *2.2. Flux-pump excitation of superconducting coils*

One of the primary constraints on the design of cryocooled HTS systems, due to the unavailability of HTS persistent joints, is the requirement for permanently active, permanently connected current leads to continuously energize the coils. This room temperature-connected thermal link typically presents the largest single heat load on the cooling system. Furthermore, high-current, high-stability magnet power supplies are bulky, costly and power-hungry. A flux pump provides a means for exciting superconducting coils inductively, breaking the thermal pathway to room temperature and eliminating the need for a high-current supply [8].

We have retrofitted a cold radial flux pump to a 2 T HTS nuclear magnetic resonance (NMR) relaxometry magnet (Figure 2), and demonstrated successful pumping to the rated 2 T field strength (130 A coil current) over a period of 2.5 hours [9]. The field stability at full field was measured to be 30 ppm (60 μT) peak-to-peak over one hour. This is insufficient for NMR, but is understood to arise from the resolution of the Hall probe used to provide feedback to control the field, and could therefore be improved through the incorporation of a $^2H$ field lock, common on NMR systems. Nonetheless, the flux pump has proved its capability by significantly reducing the heat load on the cryocooler (by a factor 4.5 in this case) and replacing the bulky high-current magnet power supply with a compact low-power unit.

Fig. 3. High-current HTS wire characterization system.

Fig. 4. Three-phase, 1 MVA, 2G HTS distribution transformer.

As the next stage of development, we aim to apply flux pump excitation to a 55 kW generator incorporating an HTS rotor. This requires effective flux pump operation over practical distances such that the flux pump exciter can be situated outside the cryostat. To this end, we have developed a number of cold and warm radial and axial flux pump designs with variable gaps, and optimized the magnetic circuit to maximize pumping efficiency across the gap [10].

### *2.3. Superconducting wire characterization*

A key prerequisite to designing large-scale superconducting devices, particularly from 2G HTS material, is to possess an accurate and detailed quantification of the underlying performance of the wire, which can vary dramatically from manufacturer to manufacturer and even from batch to batch, and which cannot be reliably extrapolated across temperature and to a lesser extent field. The strongly anisotropic and irregular nature of contemporary pinning-engineered 2G material means that a full characterization across all field angles is also required. To this end, we have developed a cryogen-free high-current HTS wire characterization system, built around a cryocooled 8 T HTS magnet (Figure 3), that enables us to perform automated measurements of the transport critical current of full wire samples across a wide range of temperatures, magnetic fields and field angles [11], acquiring up to 4,000 *IV* curves per day. The comprehensive wire data obtained on this system informs our magnet designs and operational capabilities, enables us to predict the performance of 1G wires under wide-ranging conditions [12], and allows us to fully assess wires sourced from a broad range of manufacturers for suitability for application under the specific operating conditions of interest.

## 3. Cable-based Technologies

### *3.1. Commercial Roebel cabling*

We began development of the wire-supplier neutral automated long-length production of Roebel cabling from 2G HTS wire in 2004 and commercialized the process in 2007 through General Cable Superconductors Ltd. Since then, we have continued to refine and develop the production methodology to achieve improved performance and reliability [13], while seeking to employ Roebel cable in high and/or alternating current demonstration projects aimed at proving its effectiveness in these types of applications [14,15]. At the same time, we have been building an experimentally-underpinned understanding of the electrical and mechanical properties – in particular the reduced ac losses – of this style of fully transposed cabling [16].

There are two primary stages of processing of as-supplied wire into a cable that require to be addressed: punching of the meandered strands and winding together of individual strands to form the completed cable. For each of these processes, we have devised bespoke machinery to perform continuous reel-to-reel processing of source wires of any form and architecture. We have also developed in-line characterization methods for monitoring the performance of the finished product for quality control purposes [17]. Other issues we seek to address include long-length registration of cabling crossovers, effective strand insulation and the mechanical strengthening of the resulting cable [18]. To date, we have demonstrated cabling of wires sourced from AMSC, SuperPower, Fujikura and STI. Cables up to 25 m in length (comprising 375 m of wire in 15/5 format) have been supplied to customers, and up to 40 m cables have been wound successfully. The cables have been shown to preserve the critical current performance of their constituent wires at the level of ~90% (so long as self-field effects are properly accounted for), resulting in viable kA-class conductors at 77 K.

### 3.2. HTS distribution transformer

A flagship application of Roebel cabling to a high-current ac power system lies in the demonstration three-phase 1 MVA 2G HTS distribution transformer devised [19, 20] and constructed in our Institute (Figure 4). Here, the low voltage 415 V (high current) secondary windings of each phase comprise 20 turns (19.6 m) of GCS 15/5 Roebel cable in a single layer solenoid coil designed to carry 1389 A rms (1964 A peak) at an operating temperature of 70 K provided by sub-cooled liquid nitrogen. The high voltage 11 kV primary windings each comprise 918 turns (980 m) of 4 mm wide SuperPower 2G HTS tape constructed as 24 double pancake coils and intended to carry 30.3 A rms. The overriding design goal is the reduction of ac losses to a practical level, which has been achieved [21], with residual ac losses resulting in an *electrical* efficiency of around 99.95% at full load, and 99.997% at half load. In assessing overall transformer efficiency, however, it is necessary to account for the cooling penalty of extracting heat generated at low temperature and for other heat leaks into the system such as the electrical feedthroughs, at which point a transformer of this moderate rating becomes difficult to justify on the basis of efficiency alone. Nonetheless, ac loss has been shown not to be a fundamental obstacle to commercialization of an HTS transformer based on Roebel cable. Based on the results of ac loss modelling, validated on the experimental data gained through the operation of this transformer, a 40 MVA HTS transformer design could be expected to be competitive in efficiency terms with a conventional distribution transformer, particularly if the operating temperature is dropped to 65 K.

HTS transformers cooled by liquid nitrogen in general offer a range of benefits over conventional oil-cooled transformers extending beyond bare efficiency to environmental and fire hazard reduction resulting from the more benign coolant, reduced wear and tear from the low temperature operation, and a more compact form factor than their conventional counterparts. These benefits make HTS transformers attractive to a range of niche applications where safety or transportability may be overriding considerations.

## 4. Summary

New Zealand is driving forward the global commercialization of emerging HTS technologies ranging from current leads to cabling to magnet systems. Prototypical large-scale HTS application devices ranging from magnetic resonance imaging systems to distribution transformers to rotating machines are being designed, constructed and validated in operation at the Robinson Research Institute, ready for commercialization through our industrial partners. Supporting technologies such as HTS Roebel cabling and flux pump-based brushless exciters are also being developed, assessed and proven in real-world applications.

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